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This is a final report describing research carried out on the physical processes of breakdown of unsteady boundary-layer flows at high Reynolds numbers. The research is relevant to processes occurring in dynamic stall and transition to turbulence and concerns the complex physical processes that can occur when a boundary layer separates from a rigid wall. The results indicate that very complicated responses develop in the surface pressure, in some cases leading to instability. It has been shown how the boundary layer can break down locally and lead to a process of explosive windup into a new vortex structure. The theory appears to be consistent with and explains the breakdowns observed in experiments, as well as direct simulations of turbulent and transitional flows.

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FINAL REPORT

SHEAR LAYER BREAKDOWN IN COMPRESSIBLE FLOW

AFOSR-92-J-0007

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1. Introduction

This is the final report on research performed under AFOSR grant 92-J-0007 initiated at Lehigh University in November, 1991. The grant essentially was to support a British postdoctoral student, Dr. Andrew Neish, and Professor F. T. Smith (as a consultant) of the Mathematics Department at University College London, England. Dr. Neish's research was being carried out at Lehigh University in collaboration with Professors Smith and Walker. In August 1993, Dr. Neish had to return suddenly to England due to personal problems, and the funding on the grant was subsequently substantially reduced. At that stage, the work on the project was taken up by Professor Walker and a postdoctoral student, Dr. Jun He, at Lehigh and by Dr. R. I. Bowles at University College London. This report summarizes work completed and in progress.

2. Description of Research

The objective of the research was to identify the cause and effect relationships as a boundary layer starts to break down and detach from a solid surface. This is a generic phenomenon occurring in a variety of large scale applications, such as in dynamic stall and in turbomachinery. In such realizations, the boundary layer on a portion of the aircraft is observed to abruptly leave the surface as a consequence of the adverse pressure gradient induced either by the geometry, a vortex above the airframe surface or due to a maneuver (Doligalski et al., 1994). The result of this eruption is a viscous-inviscid interaction which is usually observed to culminate in the formation of a new vortex structure. In the process, vorticity that accumulates near the surface is abruptly thrown away from the surface. Similar phenomena are found at smaller scale in laminar-turbulent transition (see, for example, Smith et al., 1991).

The objective of this research is to understand how and why such events initiate and to delineate the various stages of the process as the boundary layer leaves the surface. Most practical realizations of such events occur at high Reynolds numbers, in a range which is currently well beyond the scope of most modern computational methods which are based on direct simulation techniques using the Navier-Stokes equations. The present work is being carried out using a combination of asymptotic theory and numerical work to track the generic processes that occur as a shear layer evolves into a strong unsteady interaction.

Consider a boundary layer flow under the influence of an adverse pressure gradient. As described by van Dommelen and Shen (1982), Elliott et al. (1983) and

Peridier et al. (1991a, 1991b), eventually the vorticity that had previously diffused from the wall will start to concentrate near a location on the wall denoted as $x = x_s$; this concentration takes the form of sharp focusing proportional to $(t_s - t)^{3/2}$ near x_s as the vorticity collapses into a strong shear layer near x_s. There are various stages that can be identified in this process. As the focusing initiates, the boundary layer starts to grow significantly in a direction normal to the wall, and the first change that occurs is a local modification in the external pressure field. Traditionally, such interactions have been handled in high Reynolds number flows by invoking interacting boundary layer (IBL) concepts. In such formulations, the disturbances to the external mainstream are assumed to be small and localized and the thickening boundary layer and external flow are coupled by a Cauchy integral relating the pressure and the displacement thickness.

While the onset of interaction is correctly modeled by IBL concepts, Smith (1988) has shown that the conventional IBL soon develops a new interactive singularity, having a structure that was subsequently closely verified by extensive computational studies (Peridier et al., 1991b). A schematic of this structure is shown in Figure 1, which may be considered to be a magnified view (in the streamwise direction) of the boundary-layer structure just prior to breakdown. Here the boundary layer bifurcates locally into two shear layers (regions I and III) separated by an effectively inviscid zone (region II) above and below where the velocity profile is in general rotational. The pressure expansion near the breakdown location is of the form

$$p = p_o + T^{1/2} p_1(\xi) + T^{3/4} p_2(\xi) + \dots, \tag{1}$$

where p_o is a constant and

$$T = t_s - t, \qquad \xi = \left\{x - x_s + cT\right\} T^{-3/2}, \tag{2}$$

with t_s being the breakup time and c being the speed of the moving focusing eruptive zone. In the analysis of Smith (1988), general solutions were obtained for the central region II, and region III was found to be a critical layer centered on a vertical location at $y = y_o$. The expansion for velocity in region II is of the form

$$u = U_o(y) + T^{1/2} U_1(\xi, y) + \dots \tag{3}$$

and $U_o \rightarrow c$ as $y \rightarrow y_o \pm$.

An important result of the Smith (1988) analysis is that the basic profile $U_o(y)$ is found to satisfy the breakup criterion.

$$\int_o^\infty \frac{dy}{(U_o - c)^2} = 0 \tag{4}$$

where the bar on the integral indicates that the integral is to be interpreted as a principal value in the Hadamard sense. A jump in velocity occurs across the critical layer given by

$$J = \int_o^\infty \left\{ \frac{1}{2} U_1 - \frac{3}{2} \xi U_1 - U_1 U_{1\xi} + \Psi_{1\xi} U_{1y} \right\} \frac{dy}{(U_o - c)^2}, \tag{5}$$

and the value of J must be found through an analysis of the critical layer III. The analysis of the critical layer is complex but ultimately leads to the result that within the context of interacting boundary layer theory, $J = 0$ and the first term for pressure in the expansion (2) satisfies a relation of the form

$$\xi = -A\, p_1 - B\, p_1^3, \tag{6}$$

where A and B are constants. The analysis of Smith (1988) thus appears to give a self-consistent picture of a breakdown occurring on a focusing tangential scale, i.e. ξ, and a developing intense variation in pressure with $|p_1| \sim |\xi|^{1/3}$ as $\xi \to \pm\infty$, at either side of the interaction zone. Close confirmation of the structure has been provided by the numerical work of Peridier et al. (1991b).

The focus of the present research is on determining how the developing singularity in the IBL formulation is mitigated and, in particular, the processes and new physics involved in the next stages of the interaction. The present work has identified the next two stages in the sequence of events wherein pressure gradients normal to the surface first come into play along with the evolution of a non-linear critical layer. In the next phase a strong vortex wind-up appears to develop leading to vortex production near the surface.

First consider the initial stage which occurs just prior to the formation of a singularity in the conventional IBL formulation. It has been found that on short length and time scales, i.e.

$$\xi = O(Re^{-3/14}), \quad T = O(Re^{-1/7}), \tag{7}$$

normal pressure gradients enter the formulation in a thin region near the breakup location $x = x_s$. This gives rise to a nonlinear behavior in the critical layer III. The analysis of this problem is complex and lengthy and will not be reproduced here. It may be noted, however, that in the present study an error was found in the analysis of Smith (1988), upon which the present research is based. It was, therefore, necessary to carry out a detailed analysis of the theory leading up to the next stage in the eruptive process. A main result, however, is the derivation of an equation governing the local pressure distribution, which is given by

$$\overline{p} = p_o + \mathrm{Re}^{-1/4}\,\tilde{p}(X,T) + \ldots \tag{8}$$

where $\tilde{p}$ is found to satisfy the nonlinear evolution equation,

$$\tilde{p}_T + \tilde{p}\,\tilde{p}_x - a\,\tilde{p}_{xxx} = \tilde{\mu}\,\tilde{p}_x \,⨍_{-\infty}^{\infty} \frac{(\tilde{p}_T(s,T) + \tilde{p}\tilde{p}_x)ds}{\tilde{p}(x,T) - \tilde{p}(s,T)}\,. \tag{9}$$

Here a and $\tilde{\mu}$ are constants, the bar on the integral denotes a Cauchy principal value integral (as well as a finite part integral) and the subscripts denote partial derivatives. Equation (9) reduces to a Korteweg-de Vries (KdV) equation when the forcing function on the right side is not present (i.e. $\tilde{\mu} = 0$), but otherwise it is a non-linear evolution equation for pressure. It is referred to as an extended KdV equation. The numerical solution of this equation is to be obtained subject to matching to the previous interaction stage as $T \to -\infty$. It was necessary to develop an accurate numerical solution procedure to solve equation (9). It emerged that standard numerical algorithms for the KdV equation were not accurate enough for the present purposes and, in addition, suffered from various stability problems when the non-linear forcing function on the right side of equation (9) was introduced. A fully implicit method which is second order accurate in space and time was developed. Some representative calculated results for pressure are shown in Figures 2. In Figure 2(a), a typical calculation for pressure in the interactive zone is shown for a case with $\tilde{\mu} > 0$. It may be noted that a local maximum and minimum have formed, and this even signals the end of the extended KdV stage for cases where $\tilde{\mu} > 0$, since the integrand in equation (9) is then singular. By contrast, the case for $\tilde{\mu} = 0$ is shown in Figure 2(b). Here the pressure distribution is found to develop a strongly oscillatory behavior which spreads progressively to the right, suggesting the possibility of eventual instability for the case $\tilde{\mu} = 0$.

Some typical calculated results for $\tilde{\mu} < 0$ are shown in Figures 3. It may be noted in Figure 3(a) that an instability evidently starts to develop. As time increases, the instability develops to shorter wavelengths as indicated in Figure 2(b). It has been possible to carry out a stability analysis for equation (9), and this theory predicts the evolution of high frequency instability of equation (9) for all $\tilde{\mu} < 0$. Calculated growth rates for the instability are shown in Figure 3(b), where it is evident that once initiated, the instability grows rapidly and, in fact, soon enters a nonlinear stage.

At present, work on a paper describing this phase of the break-up process is ninety-five percent complete (He, Walker, Bowles and Smith, 1995). Detailed numerical studies have been produced for the cases of positive μ, negative μ and zero μ. It is found that each case possesses distinct characteristics. The first case of positive μ leads into a further finite time irregularity and the second shows a strong secondary instability. Thus before the traditional soliton-containing stage normally associated with a KdV equation can be reached, more new physics come into play in general. The special case of zero μ, however, continues to large-scale times, acquiring then an intriguing structure with solitary and traveling waves. A subsequent stage is implied thereafter on longer timescales, and it comprises a long-scale/short-scale interplay between the original interacting boundary layer system and multiple local Euler systems for zero μ. In the case of positive μ by contrast, the subsequent stage is considered in a second paper (Smith, Bowles and Walker, 1995) and is due to essentially the formation of an increasingly strong winding-up vortex within the nonlinear critical layer, together with faster time scales and still shorter length scales. The further increase or decrease of the vortex strength is studied in the second paper (Smith et al., 1995). It is interesting to note that the criterion for the occurrence of the winding-up vortex here concerns the onset of a maximum/minimum in the scaled local pressure variation. Along with an integral condition on the local velocity profile, given by equation (4) for the effective local phase speed, this theoretical criterion is met fairly closely in the transition experiments of Nishioki et al. (1979), as quantitative comparison in Smith and Bowles (1992) show. In addition, the criterion is also apparently met in the computations of Sandham and Kleiser (1991). This criterion, according to the above evidence corresponds to the formation of the so-called "first spike" during certain transition paths. Work has also been completed indicating the extension of the present theory to three dimensions and the implications for computational studies of dynamic stall and transition.

The second paper is also at this stage ninety-five percent complete (Smith,

Bowles, Walker, 1995). This concerns deepening dynamic stall and transition in a boundary layer or related unsteady flows. The study follows the nonlinear evolution of the spanwise vortex produced when the local wall pressure develops a maximum, or minimum, subsequent to the finite time breakup of an interacting boundary layer and the impact of normal pressure gradients. The evolution is controlled by an inner/outer interaction between the effects of the normal pressure gradient, and the momentum jumps across and outside the vortex, which is situated near the strong inflection induced in the mean flow. Analysis and associated computations point to two distinct trends in the vortex response, depending mainly on a parameter gauging the relative strengths of the above effects. The response is either an explosive one, provoking greatly enhanced wind-up, growth and pressure in the vortex, or it is implosive, causing the vortex to shrink and virtually empty itself through an unwinding, leaving little local pressure variation. The theory is thought to explain the relative strengthening in a weakening of spanwise vortices observed in experiments and direct computation of turbulent and transitional flows. The work also confirms the suggestions of earlier theories that the pressure (including its local extrema) provides a good measure of the local vortex characteristics, and it suggests a means of handling vortex interactions in a rational manner.

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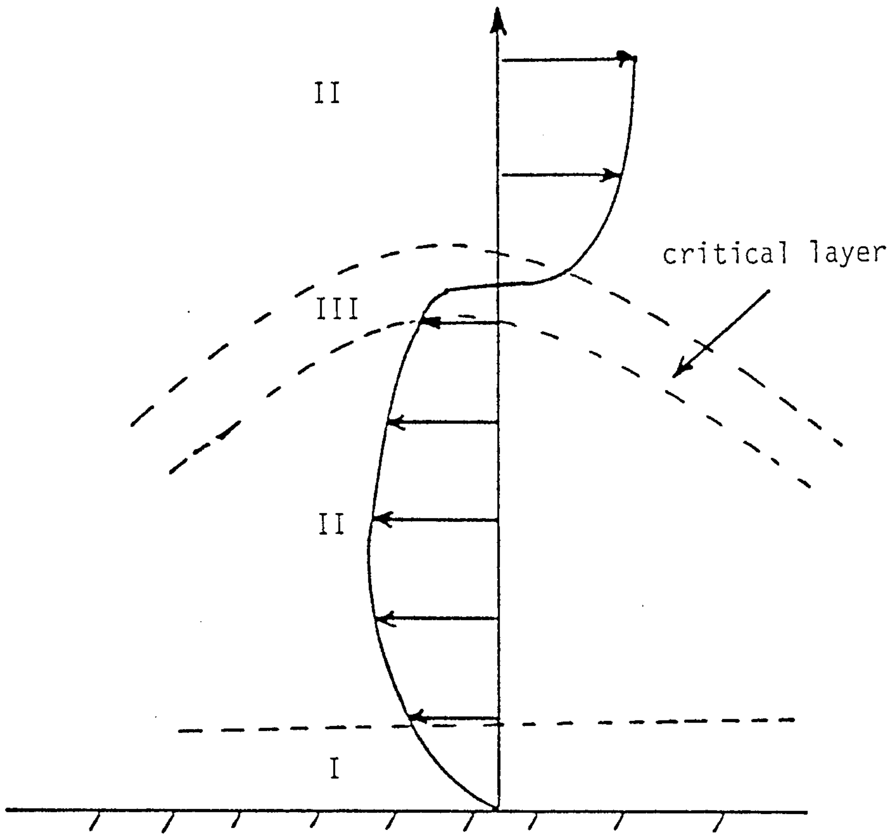

Figure 1. Schematic of the three-zone region associated with the terminal state of unsteady, interacting boundary layers (Smith, 1988).

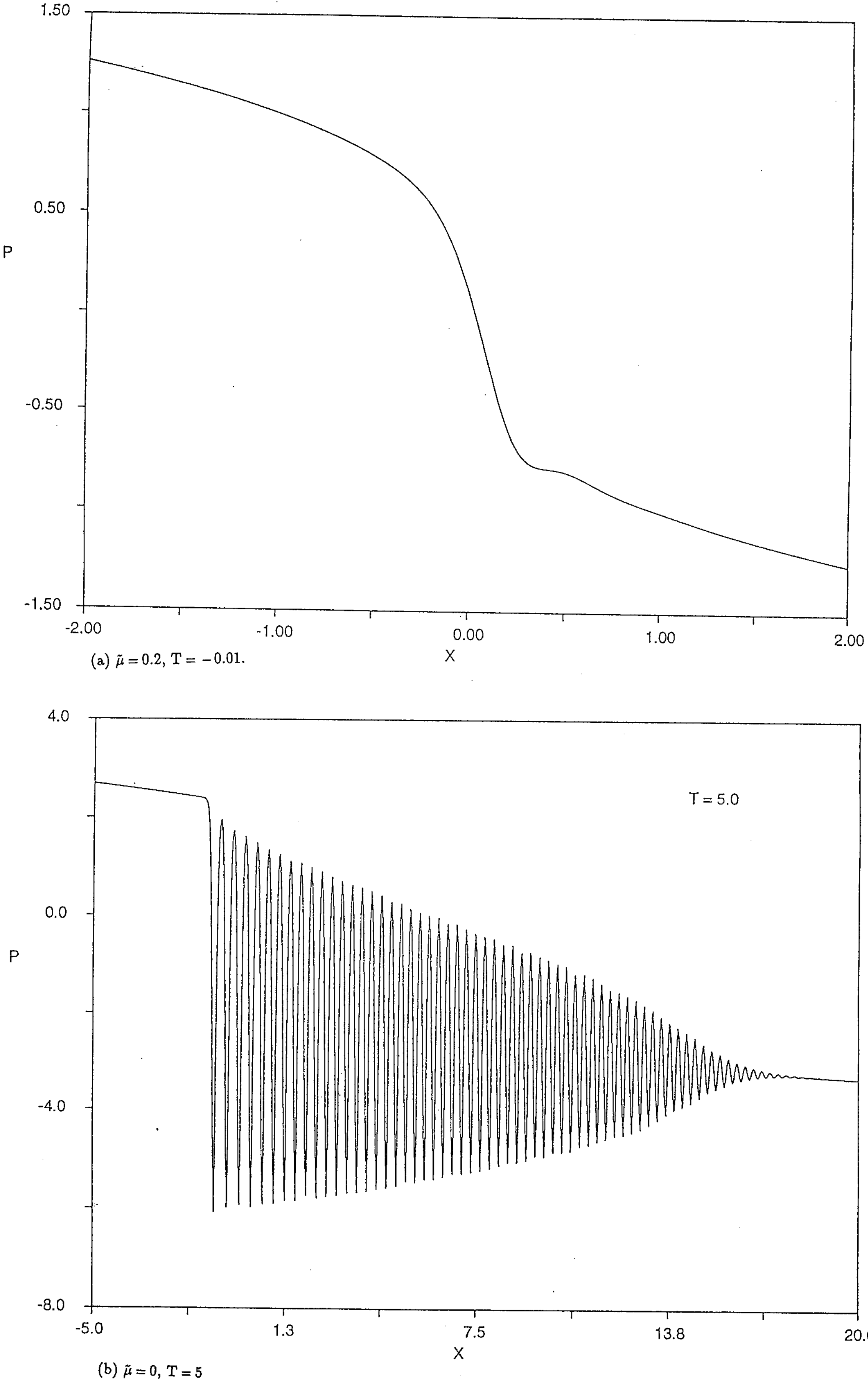

Figure 2. Calculated pressure distribution in the interaction zone in the extended KdV stage.

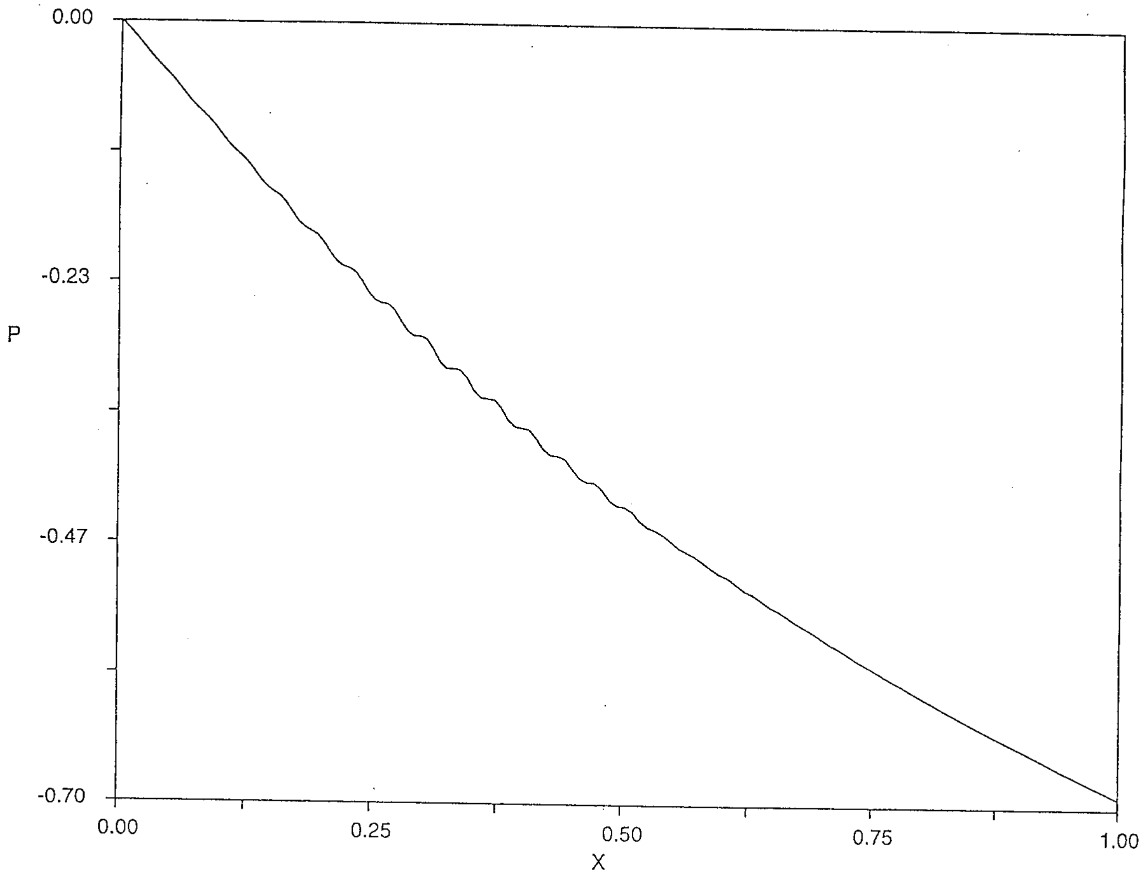

Figure 3(a). Calculated results for pressure for $\tilde{\mu} = -0.1$ at $T = -0.975$.

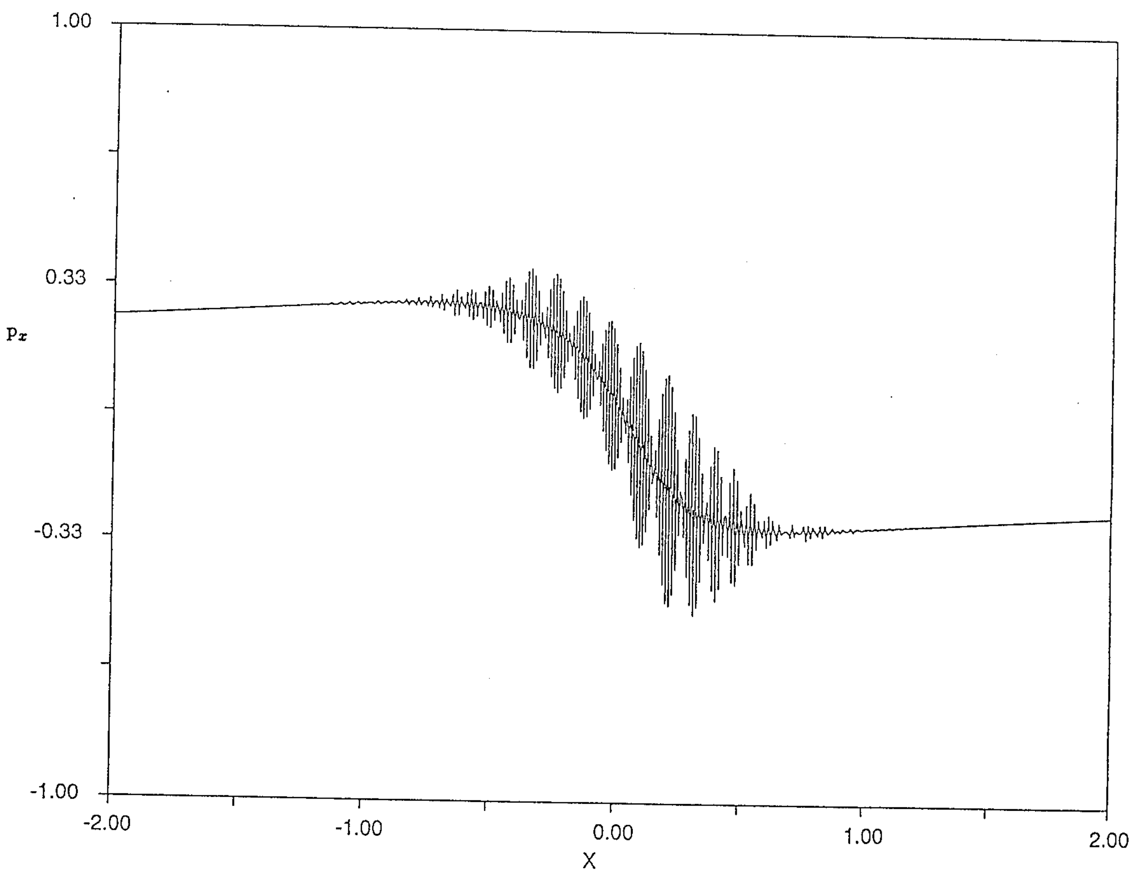

Figure 3(b). Calculated results for p_x at $t = -0.973$.